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STORAGE

STUDIES IN SOIL MOISTURE, PART I

BY

BERNARD HOWELL WILSDON, B.A. (Oxon.), I.E.S.

Agricultural Chemist to the Government of the Punjab.

1953

AGRICULTURAL RESEARCH INSTITUTE, PUSA

PRINTED AND PUBLISHED FOR
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PREFACE

THE appearance recently of a paper by B. A. Keen (*J. A. Sc.*, Vol. X, 44, 1920), which gives an admirable résumé of the work so far published on the mportant subject of soil moisture, has caused me to consider it advisable to give a preliminary account of the lines of work on this subject which have been developed at Lyallpur since 1917. It is probably unnecessary to refer here to the overwhelming insistence of the demand in a Punjab irrigation colony for research into the problems presented by the agriculture of such tracts, which involve the elucidation of the factors controlling the movement of moisture in the soil. That any investigation into these problems involves an attack from many directions is obvious when the complexity of the subject is considered. But to wait for the final convergence of a series of independent lines of investigation unduly postpones the publication of ideas and results which may be of use to workers in the subject and which may interest others who may give assistance. I therefore make no apology for the fact that much of the work described hereinafter is at present very incomplete beyond the statement that I hope at not far distant dates to continue this paper in a series of parts, describing in detail the work which has been performed in each division of the subject.

I wish also to take this opportunity of thanking my assistants by whom the practical part of the work has almost entirely been conducted and in collaboration with whom individually subsequent papers will be published. In particular I wish to refer to Dr. Ramji Narain, who has worked on the absorption experiments; to Bh. Balwant Singh, B.Sc., and L. Parmanand, M.Sc., who have respectively performed most of the work on the compressibility and partition experiments; and last but not least to those whose work has been incidental, or is not yet ready for publication, but who have materially assisted in the progress so far attained, of whom in particular Bh. Jaggat Singh, M.Sc., Assistant Professor of Chemistry, for his work on the vapour pressure measurements, and L. Mukand Lal, L. Ag., for his work on the boring experiments, are to be mentioned.

LYALLPUR, PUNJAB. B. H. WILSDON.

STUDIES IN SOIL MOISTURE, PART I.

BY

BERNARD HOWELL WILSDON, B.A. (Oxon.), I.E.S.,

Agricultural Chemist to the Government of the Punjab.

[Received for publication on 25th September, 1920.]

Introductory.

The importance of our arriving at definite knowledge of the factors which control the movement of soil moisture will be most evident to those acquainted with conditions of irrigation farming in arid tracts. Not only does the productivity of vast areas, as in the Punjab, depend on the proper utilization of the water which irrigation engineering provides for the cultivation of previously desert tracts, but the future fertility of the soil, and its power of supporting an ever-increasing population, are dependent on the methods adopted, for by excessive irrigation, on the one hand, the water-logging of the soil is a not far distant prospect, and an accomplished fact in certain areas, while, on the other, a too parsimonious economy may render the soil saline. Very simple considerations will serve to emphasize these facts.

In the case of the Lower Chenab canal system, which irrigates the tract of country lying between the Chenab and Ravi rivers, records of the level of the sub-soil water table have been maintained by the Punjab Irrigation Department since the canal was constructed. The general form of the water table previous to the construction of the canal, was, as far as can be ascertained from the records existing, saucer-shaped. It is now characterized by marked ridges under the main canal to a distance of about sixty miles from the head works. This is obviously due to direct seepage from the channel and it is in this tract that actual water-logging of the soil has taken place. Below this point there are no marked ridges, but the sections show that there has been a general rise

in the water table. This may be explained by supposing that the canals, which by now are much reduced in size, do not lose so much by seepage, and do not, therefore, produce that marked influence locally which occurs in the higher reaches. It is of great importance, however, to arrive at definite conclusions on this subject. The tendency has been to refer the whole responsibility for the general rise of the water table to seepage from the channels. In fact, Government has seriously considered the feasibility of waterproofing both projected and existing canal systems, but it is obvious that the enormous expenditure which would be involved in such an attempt would be wasted if it were afterwards found that the remedy only partially checked the rise.

Fig. 1, which has been adapted from diagrams published in a paper by C. G. May (*Punjab Engineering Congress Report*, 1918), shows a sketch map of the canal system, and four transverse sections at the points indicated with the water table levels at different years are shown in Fig. 2. In sections *b*, *c*, and *d*, there are no indications of ridges deu to seepage from channels such as are xhibited in *a*.

The deepening of the sub-soil stream may be due in part to heading up, caused by the inflow in the area considered being greater than the outflow, and also to the percolation from the surface, which we may suppose will be uniformly distributed over the whole area. Assuming the sub-soil to be uniform, we can obtain an approximate idea of the magnitude of the heading up effect by calculating the gradients round the circumference of an area, and assuming values for the transmission constant of the sub-soil and the depth of the sub-soil stream, the discharges can be calculated. This has been done, but it is found that, even assuming the soil to be composed of coarse sand, the heading up effect does not amount to much more than 1 per cent. of the total rise for a depth of sub-soil stream of 100 feet. We shall, therefore, be justified in referring the rise in the sub-soil at any place almost entirely to the percolation flowing from the surface immediately above it.

By measurement of the contour maps for different years referred to above we can now calculate the volume of water added. In the area cut off by the lines bb′—cc′ this amounts for the 10 years 1905–1916 to $51{\cdot}5\times10^{10}$ c. ft. and the area cc′—dd′ $124{\cdot}1\times10^{10}$ c. ft. Assuming the pore space of the soil to be 40 per cent., this increased volume of saturated soil corresponds with quantities of water added of $20{\cdot}60\times10^{10}$ and $49{\cdot}64\times10^{10}$ c. ft. To provide this enormous volume of water in 10 years we should require discharges of 653 and 1,574 cusecs respectively. These figures expressed as cusecs per square mile come to 0·65 and 0·59 or, say, 0·62 cusecs. The gross area commanded by the canal is 3,360,000 acres or 5,250 square miles, so the total percolation from

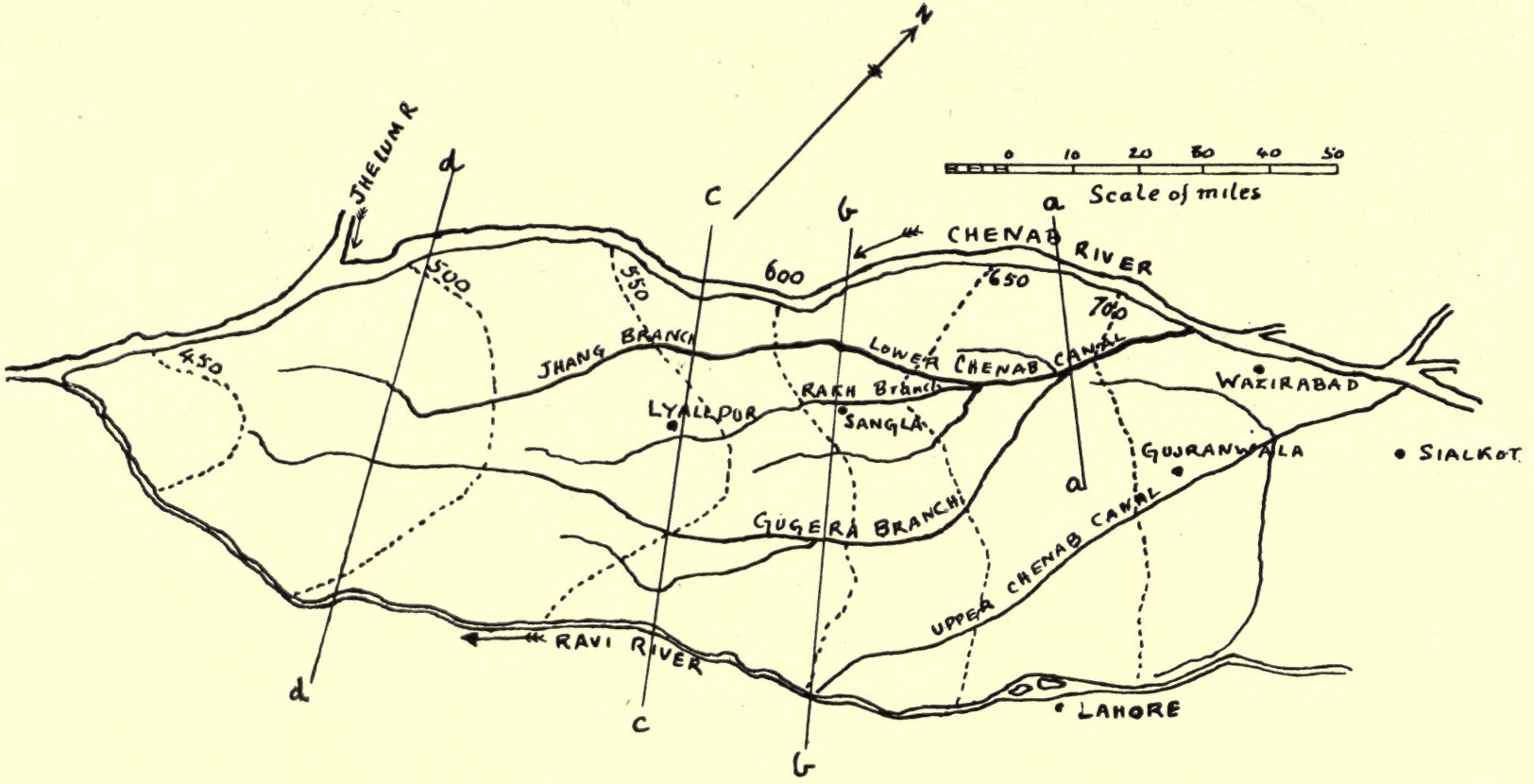
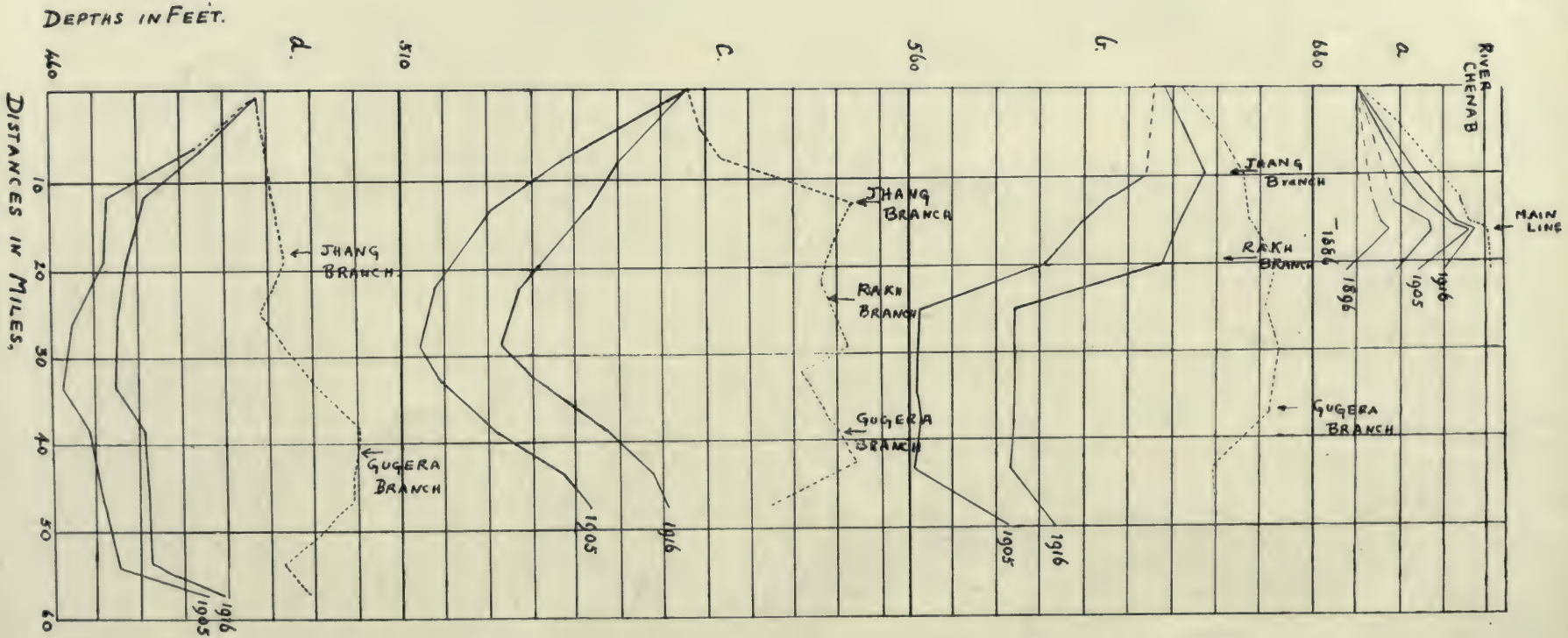


Fig. 1. Upper and Lower Chenab canal systems, showing contours of sub-soil water table at 50 feet intervals and four lines of wells referred to in text.



Fig, 2. Cross sections of the Ravi-Chenab Doab, showing water table. The verticle scale is the same throughout, but ,different base lines have been adopted.

the canal system is something in the neighbourhood of 3,255 cusecs and is probably greater than this. The average discharge of the canal may be taken as about 8,500 cusecs throughout the year, so the losses to the sub-soil represent 38 per cent. of the water taken in at the head works. According to the statistics published by the Canal Department, of this, an average of about 17·5 per cent. is lost by absorption in the main line and branches. This leaves about 20 per cent. to be accounted for by loss from distributaries, watercourses and fields, *i.e.*, 1,700 cusecs.

Taking the average irrigated area as 2,250,000· acres, or 3,515 square miles, this loss represents a discharge of about 0·5 cusec per square mile of irrigated area throughout the year.

We have now to try to apportion these losses between the distributaries, watercourses and fields. Kennedy[1] estimated losses from distributaries at 6 per cent. and from watercourses 21 per cent. These figures were obtained by actual measurements of the sinkage of water ; it should, therefore, be borne in mind that his figures, representing, as they do, losses due to evaporation as well as percolation, cannot be compared with those based on the actual additions observed in the sub-soil. The losses from the fields he calculated by considering the transpiration ratio of crops, and no great reliance can be placed on this estimate; even if we accept Kennedy's figures for the losses in distributaries, we see that there is a residual loss of about 14 per cent. This loss which takes place in the fields and watercourses will not be affected by the adoption of waterproofing and would appear to be of such a magnitude as to remove even the partial mitigation of the evil of water-logging by this method from the sphere of practical politics.

That there must be a considerable amount of percolation from the fields themselves is obvious when we consider that the irrigation water applied in the field is not pure, but contains a considerable amount of saline material. The average of a large number of analyses made at Lyallpur shows that the total soluble matter in irrigation water is about 12 parts per 100,000, and is almost entirely composed of the sulphate, chloride and carbonate of sodium. We shall therefore be well within the mark in assuming that ten parts of sodium salts per 100,000 of water represents the average value. The total ash of the crops removed from the field contain relatively small amounts of sodium salts, so the only method by which this salt can be removed is by percolation to the sub-soil. The following table gives the amount of irrigation water generally used to mature an average crop, the amounts of sodium

[1] Kennedy. *Pb. Irrign. Branch Papers*, No. 10 (1905), p. 47.

salts added, and the total mineral matter removed from the field with the crop.

Crop	Irrigation in inches	Sodium salts added, in tons	Total ash
Wheat	10·0	0·100	0·094
Toria (*Brassica campestris*)	10·0	0·100	0·030
Cotton	22·5	0·225	0·175

The above crops represent an average three years' rotation, so we may put the average annual gain of sodium salts per acre at between two and three hundredweights.

In most cases the annual application of water will be considerably in excess of what is given above. The content of sodium salts in the sub-soil water of the tract we are considering is between 12 and 24 parts per 100,000. Only in one case has a figure been obtained below 12 and this was for a well near Sangla Hill where there is a considerable out-crop of rocks. In some cases, particularly in a well which has been unworked, the salt content rises high above these figures, but this is probably due to other causes. If we could obtain a reliable average figure for the sodium salt content of the sub-soil water, it should be possible to form an idea of the amount of water percolating to the sub-soil.

To the 2,258,000 acres of irrigated land in the colony between 0·1 and 0·2 tons of sodium salts are added annually per acre, that is about 337,000 tons.

The factor for the conversion of cusecs per year of 365 days to tons of water is 878,400; assuming the sub-soil water to contain 20 parts sodium salts per 100,000 and the irrigation water 10 parts, we have for the total sodium salts percolating to the sub-soil

18 per cent. of 8,500 cusecs containing 10 parts per 100,000
X(20 per cent. of 8,500 ,, ,, ,, ,,)
337,000 tons from fields.

The concentration will consequently be

$$\frac{\frac{8{,}500\times878{,}400\times10}{100\times100{,}000}\left\{20X+18\right\}+337{,}000}{878{,}400\times3{,}255}=\frac{20}{100{,}000}$$

from which $X=\frac{2}{3}$ nearly

Thus on the above supposition the fields would be responsible for 1/3 of the percolation losses taking place after the entry of water into the

distributaries. Before much weight can be attached to such considerations as these, a more detailed investigation, both of the soluble matter contained in sub-soil waters, as also of the salt contents of plant ashes, will be required. Moreover, the determination of the salt concentration of the soil solution will only be of use if it is possible to determine at the same time the concentration of the "free" solution. The salt content of the water percolating from the fields calculated as above works out to only 1 part in 738, which seems much too low, but it must be remembered that the method of calculation does not assume that this figure represents the actual concentration of the solution draining from fields but only the average concentration for the year. Work on this aspect of the problem is being continued.

In the light of these very approximate considerations alone we see that the future of irrigation agriculture can be predicted, and the best practical methods can be devised, only on the basis of a clear understanding of the mechanism of water movement in the soil. It must also be borne in mind that the soluble matter contained in the water will play a large part in determining these actions, and must be considered, not only in the more theoretical aspects of the case, but also in the field. The mere fact that good crops may be grown on one-third the usual amount of irrigation water (*cf.* the work of Howard)[1] is no proof that it is good agriculture until experience has shown that the soil is not impaired thereby, and this may take many years to demonstrate. The experience of the cultivator, with his traditions mainly grounded on "chahi" (well) irrigation, which involves the use of a much more saline water, leads him to put as much water on the soil as he can, and is to be explained by his instinctive fear of his soil becoming saline. Again, we must face the possibility that the adoption of most extensive waterproofing of channels may, at the best, only postpone the day when the introduction of an elaborate soil drainage system will become a necessity for the continued cultivation of the soil. In the meantime, the elucidation of the conditions which determine the movement of water in the soil, will not only enable us to place methods of economy on a scientific basis, but we shall also gain knowledge which will be essential in devising satisfactory remedial measures for the cure of both water-logging and salinity.

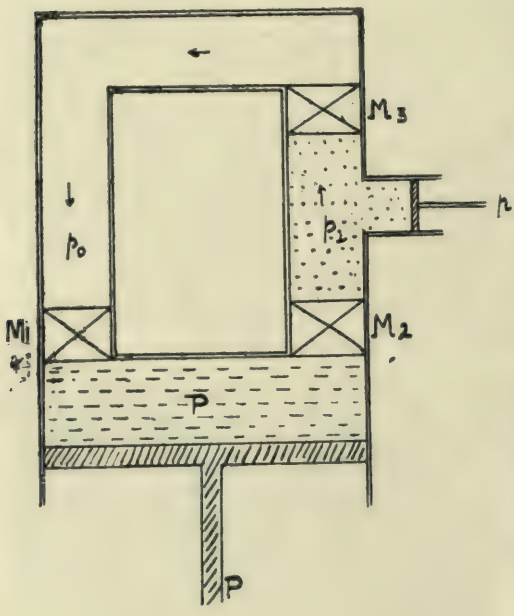
In what follows a theoretical treatment of the factors concerned in the movement of the soil solution is first given.

[1] Howard. *Ag. J. India*, XI (1916), p. 14; and *J. R. S. A.*, LXVIII (1920), p. 555.

(§ 2) Equilibrium conditions of forces operative in the soil.

In order to obtain as clear a view as is possible of the conditions of equilibium of the various forces which will be operative in the soil in determining its behaviour with water, we may best consider a thermodynamic cycle involving the transference of a quantity of water through the various phases in which it exists. This will be done by the method of the osmotic circuit devised by Calendar (*Proc. Roy. Soc.*, A Vol. 80 (1908), p. 466), which has the advantage that the precise limits of the integrals developed can be readily seen.

Considering first the case of colloid, pure liquid and vapour phases, we can magine an arrangement such as is shown in Fig. 3 whereby the circulation of a quantity of water is maintained at constant temperature by the action of perfectly efficient and reversible engines, M_1, M_2 and M_3. M_1 deals with the work involved in transferring water from the vapour phase, which is maintained at the saturation pressure for the temperature considered, to the colloid which is kept at constant volume by the pressure applied to the piston P. Similarly, M_2 extracts the water from the colloid and delivers it at the pressure p_1 which is supposed to be determined by the tension of the water films in the soil and represented by the pressure on the piston p. The third engine brings the pressure of the vapour to the saturation pressure p_0. Under these conditions the work performed by the three machines must sum up to zero, and can be written down as follows,



$$\int_{p}^{p_0} X dp + \int_{p_1}^{p} W dp + \int_{p_0}^{p_1} V dp = 0 \qquad (1)$$

Here X, W, and V represent the increase in the volume of the phases, to which they refer, which will result from the addition of unit mass of the water at the particular pressure involved. We consequently require to know the

values of X, W, and V as functions of the pressure. For V, we may put R′T/p assuming that the vapour obeys Boyle's Law, R′ representing the ordinary gas constant, R=1·98 calories, divided by the molecular weight of the vapour. Or, since we must consider all the pressures involved in the cycle as including the atmospheric pressure, we should be more accurate to use the values obtained by Regnault for the partial pressures of water vapour in air, assuming of course that Boyle's Law applies and that the partial pressure relation is obeyed. We may thus write, as suggested by Berkeley, Hartley and Burton [*Phil. Trans.*, A 209 (1909), p.177] $V=p_o/\rho_o p$.

For W we may employ the relation $W=W_0(1-\alpha p)$ in which we may assume the compressibility α constant.

For the variation of X with the pressure we have no certain data, and this will have to be determined experimentally for each soil examined. Ostwald has shown that an expression of the form $p=KC^n$, where C is the volume concentration, and the exponent n lies between 1·5 and 4·0, agrees with experimental determinations of the swelling pressure p over wide ranges. By differentiating this expression with respect to p and V we get

$$\delta_v/\sigma'_p=-k'p^m$$

where the exponent is equal to $n-^1/n$ and must consequently lie between 0·33 and 0·75. As will be shown later, this relation can be tested by density determinations of soils suspended in liquids of known osmotic pressure, or, more simply, by density determinations of soils of known water contents in solvents in which water is insoluble.

Substituting these expressions in the integrals, and integrating by parts we obtain

$$mk'\ (1/p_o^n-1/p^n)+W_o[(p-1/2\alpha p^2)-(p_o-1/2\alpha p_o^2)]+R'T\ \lg\ p_1/p_o=0 \quad (2)$$

As an approximate solution of this equation, instead of considering X and W as functions of the pressure we may write X′ and W′ to represent the *mean* values of these factors within the limits of the integrals. We thus get

$$X'(p_o-p)+W'\ (p-p_1)=-RT\ \lg\ p_1/p_o \quad (3)$$

or neglecting p_o which will be small in comparison with p, we obtain

$$W'p_1-p(W'-X')=-R'T\lg p_1/p_o \quad (4)$$

We thus see that when the term on the right becomes zero, *i.e.*, when the vapour pressure of the soil is equal to that of the saturated atmosphere,

$$W'\ p_1=p\ (W'-X')$$

This means that if free water is present in the soil its moisture content when in equilibrium with a saturated atmosphere will be determined by the hydrostatic pressure of the liquid films as well as by its colloid content and the specific properties of the colloid. This point is of importance in connexion with the significance which must be attached to the measurement of the Hygroscopic Coefficient of soils, and will be dealt with again after the discussion on film tension. It may also be pointed out that a further term should be introduced for influence of the size of the colloid particles on their swelling pressure. Thus if T represents the interfacial surface tension between colloid and liquid, the effective swelling pressure will be reduced by an amount which will vary as $2T/r$, where r is the radius of the colloid particles and will be a function of their water content. Actually, since any measurements of the value of P which it will be possible to make in a soil must also include the effect of variation of the size of the colloid particles, no advantage will result from separating these factors.

We may now introduce the additional complication involved in the fact that we have to deal with a solution instead of a pure solvent. This may be

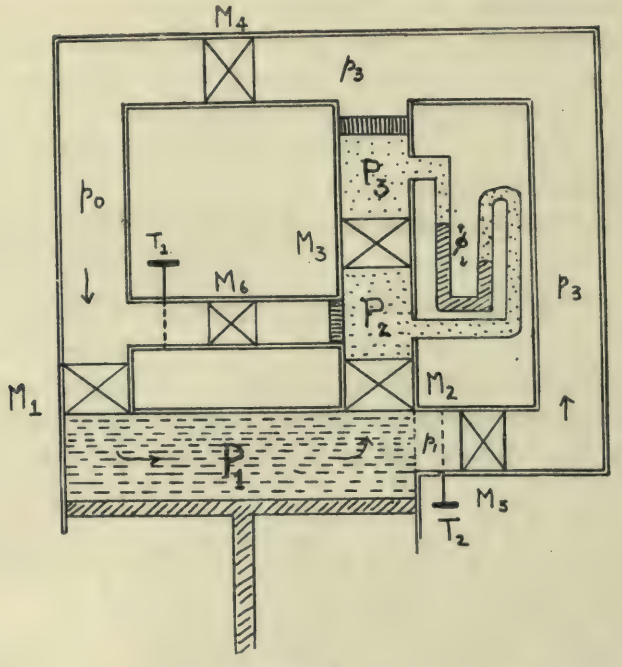


FIG. 4.

done in a similar manner by employing an extra machine to deal with the solution. (Fig. 4.) M_2 now delivers water from the colloid to the solution

at its osmotic pressure P_2, while M_3 reduces its pressure to the point demanded by the film curvature, and, as before, M_4 brings the vapour to the pressure of the saturated atmosphere. The work terms will consequently be

$$\int_{P_1}^{P_0} X dp + \int_{p_2}^{p_1} V dp + \int_{p_3}^{p_2} V dp + \int_{p_0}^{p_3} V dp = 0 \qquad (5)$$

The approximate solution of which will be, neglecting the term involving p_0

$$p\,(U^1 - X^1) - p_2 U^1 + U^1(p_2 - p_3) = R'T \lg \frac{p_3}{p_0} \qquad (6)$$

$p_2 - p_3$ is the same as the hydrostatic pressure due to film tension, and in order to simplify our notation may be written ϕ: p_2 is the osmotic pressure of the solution, measured under the pressure of its own vapour and the partial pressure of the atmosphere, and will in what follows be denoted by π. p_1 is the swelling pressure of the colloid in equilibrium with the solution, and will be denoted by ψ Rewriting the equation with these symbols we have

$$\psi\,(U^1 - X^1) - \pi U^1 + \varphi U^1 = R'T \lg \frac{\phi\pi}{p_0} - R'T \lg \frac{1\,\pi\varphi}{p_0} \qquad (7)$$

where the symbol $\lg \frac{\pi\phi}{p_0}$ refers to the vapour pressure of the liquid of osmotic pressure π under the hydrostatic pressure ϕ. Since, however, it can easily be shown by short circuiting the colloid and placing P_0 in connexion with P_2 through another machine as shown in the diagram, that $\varphi U^1 - \pi U^1 = -R'T \lg \frac{p\pi\varphi}{p_0}$ we get the result that for all values of ϕ above zero, $U^1 - X^1 = 0$

If this is true approximately, and actual measurements of the variation of X and U with the pressure will have to be made before the result can be accepted, it means that the moisture content of a soil in equilibrium with an atmosphere of any degree of saturation with water vapour will be determined by the osmotic pressure of the "free" soil solution, and the pressure exerted due to film curvature. This may be made clearer by considering the cycle when the solution is short circuited, *i.e.*, when M_2 is made to deliver at the pressure P_3 in Fig. 4. The work terms will be

$$\int_{p_1}^{p_0} X dp + \int_{p_3}^{p_1} W dp + \int_{p_0}^{p_3} Y dp = 0$$

Whence converting into the new notation and remembering that $p_3 = \pi - \phi$ we get, from (6) above,

$$\psi\,(W^1 - X^1) + \varphi W^1 - \pi W^1 = R'T \lg p\,\pi\,\varphi/p_0 = \psi\,(U^1 - X^1) - \pi U^1 + \varphi U^1$$

and,

$$(\psi - \pi +)(U^1 - W^1) = 0 \qquad (8)$$

Thus the swelling pressure of the colloid must be equal to the osmotic pressure, minus the hydrostatic pressure due to film curvature. This equation together with (3) will be the most convenient means of testing the approximate truth of the relations deduced. We may now consider the factors contained in the foregoing equations with a view to finding how far they are susceptible of practical measurement.

(§ 3) The hydrostatic pressure of "free" water in the soil.

As is well known, the work of Briggs[1] resulted in a very general acceptance of the hypothesis which views the soil as a collection of crystalline particles at the points of contact of which "free" water is held by the surface tension of the liquid. Lately, however, the extension of our knowledge of the properties of colloids, and the demonstration of the importance of these properties in explaining absorption phenomena in soils, has necessitated a modification of this originally simple view. It may be pointed out, however, that if any "free" water exists in the soil, the hypothesis of Briggs may be pursued to its ultimate conclusions. The applicability of the relations deduced will obviously depend on the strictness with which experimental facts justify the assumption which regards it possible to consider a soil composed of particles of widely varying sizes and shapes mixed in varying proportions as statistically built up of a collection of equal sized spheres. The work of Slichter and King,[2] and the more recent work of Green and Ampt,[3] shows that such assumptions are fairly well justified as regards the average diameter of the particle and the average cross section and length of the pore spaces. It does not seem unreasonable therefore to suppose that a similar assumption will be justified as regards the average diameter of the soil particles and the number of contacts per sphere. Keen[4] has used the relations deduced by Slichter to calculate the probable capillary rise in soils of various degrees of coarseness, on the assumption that the soil may be regarded as a collection of fine capillary tubes, but himself points out that his treatment does not explain the fact that the moisture content of the soil varies with the height above the free water surface. Actually, we have not to deal with a height in a column of soil throughout which the soil is completely saturated with water, but with a gradually decreasing

[1] Briggs. *U. S. Bureau of Soils Bullet in* 10.
[2] Slichter and King. 19*th Rep.* (1899), *U. S. Geol. Survey*, Pt. II.
[3] Green and Ampt. *J.A.S.*, IV (1911-12), p. 1 and V (1912-13), p. 1.
[4] Keen. *J.A.S.*, IX (1918-19), p. 396.

concentration. Moreover, it is obvious that it is the distance above the point at which a soil is *saturated* with water which is of importance in practical agricultural considerations. Thus, according to Keen, in a soil composed of particles with diameters ranging from 0·01 to 0·002 mm., the point at which water would completely fill the interstices of the soil, *i.e.*, the point up to which the soil would be saturated, would be 150 feet above the level of water in a well. This estimate although admittedly to be regarded as a maximum value is so much at variance with experience both in the field and the laboratory, that, despite a consideration of the factors which would tend to reduce the height, such as irregularity in the shape of soil particles, the trapping of air in the soil interstices, and the closing of pores by the swelling of soil colloids, it is probable that a more reliable estimate might be formed by considering the problem from another point of view.

If we consider the soil to be composed of equal sized particles, we may suppose the volume of the water held at the points of contact to be that generated by the revolution of the meniscus about the point of contact. We shall probably be sufficiently accurate if we take, as a first approximation, the form of the meniscus to be the arc of a circle which touches the two spheres. We may thus express the volume of water held at the point of contact as a function of the angle, 2θ, subtended at the centre of the soil particle by the radii drawn from the point of contact of the spheres and the tangent to the meniscus. This relationship gives for V, the volume of water per contact, the expression (see Appendix)

$$V = \frac{8\pi a^3 \sin^4\theta}{\cos^2 2\theta}\,[1-\tan 2\theta\,(\pi/2-2\theta)] \qquad (1)$$

where a is the radius of the soil particle.

The film tension, ϕ, at a curved surface will be, $\varphi = 2\gamma\left(\frac{1}{r_1}-\frac{1}{r_2}\right)$ (2)

Expressing r_1 and r_2 in terms of θ we have,

$$r_1 = \frac{a\,(1-\cos 2\theta)}{\cos 2\theta} \qquad (3)$$

$$\text{and } r_2 = \frac{a}{\cos 2\theta}\,[\sin 2\theta + \cos 2\theta - 1] \qquad (4)$$

$$\text{Consequently, } \phi = \frac{2\gamma\cos 2\theta}{a}\,\frac{\sin 2\theta + 2\cos 2\theta - 2}{(1-\cos 2\theta)(\sin 2\theta + \cos 2\theta - 1)} \qquad (5)$$

When $1/r_1 = 1/r_2$, φ vanishes: this means that the pressure immediately inside the film, and outside, will be the same. Neglecting the influence of

gravity, the point at which this takes place should represent the moisture holding capacity of the soil for free water. Thus when $1/r_1=1/r_2$,

$$\frac{\cos 2\theta}{a}\ [\sin 2\theta + 2\cos 2\theta - 2]=0 \qquad (6)$$

This equation when solved gives the values $\theta=0$, or $\tan\theta=1/2$, whence $\theta=26^\circ\ 33'$ nearly.

From the values of V it will now be convenient to calculate the moisture as a percentage on the weight of soil. For this we must know the number of contacts made by each soil particle, and this number will vary with the degree of packing. The number of particles per 100 grams of soil will be given by $100 \div 4/3\pi a^3 \rho = 31{\cdot}25/\ \pi a^3$ taking p the density of the soil as 2·4. If c=the number of contacts per sphere, then, the number of contacts per 100 grams of soil will be $n=31{\cdot}25/\pi a^3 \times \frac{c}{2}$ since each contact comes in twice. Then, since $M=n\ V\sigma$, where σ =the density of the liquid, which, for the present purposes, may be taken as unity,

$$M=125c\ \frac{\sin^4\theta}{\cos^2 2\theta}\ [1-\tan 2\theta\ (\pi/2-2\theta)] \qquad (7)$$

Thus we see that for a given moisture content θ is independent of the size of the soil particles. Consequently all soils which are packed to the same extent should have the same moisture holding capacity for "free" water. Thus taking the value of c as 12 (*i.e.*, trigonal packing) and substituting the value of $\theta=26^\circ\ 33'$, found in equation (6) above, we obtain the value M=23·46. It is remarkable that this figure should be approximately the same as that which occurs in the empirical relationship shown by Briggs and Shantz to connect the Moisture Holding Capacity and the Hygroscopic Coefficient of soils, *i.e.*, (Moisture Holding Capacity)=(Hygroscopic Coefficient)×4·2—21. Between different soils of the same moisture content and the same packing, the film tension will vary inversely as the radii. Again, if we suppose that the "constants" defined by American investigators as the Hygroscopic Coefficient, the Wilting Point, the Mechanical Equivalent, *et cet.*, represent concentrations of moisture for which the film tension has definite values, and, if we assume the osmotic concentration of the free water the same for all concentrations of water, it is easy to see that a given ratio in the soil is independent of the size of the particles

$$\frac{p}{p_1}=\frac{\phi}{\phi_1}=\frac{f(\theta)}{f(\theta)}$$

Therefore the ratios between the moisture contents of soils under conditions adopted to define the soil "constants" should be independent of the

mechanical constitution of the soil as has been shown by Briggs and Shantz.[1]

It must be remembered that these considerations neglect entirely for the present the influence of the colloids of the soil in determining the "bound" water or the size of the particles. An attempt will be made to introduce this factor later; the conclusions drawn in this section will only hold for "free" water, (not solution) in soils, the sizes of whose constituent particles are independent of the moisture content. An objection has been raised by Trouton[2] to the employment of considerations based on surface tension when the radius of curvature of the film approaches molecular dimensions. It does not appear, however, that this will invalidate the relations deduced for the concentration of moisture above a certain limit. Thus with clay particles of radius r=·0002 cm. for a moisture content of free water of 1·64 per cent. (θ=12) the values of r_1 and r_2 are respectively $1{\cdot}2 \times 10^5$ cm. and $9{\cdot}3 \times 10^5$ cm.

We may now consider the capillary rise in the light of these deductions. For the relationship between the vapour pressure and the hydrostatic pressure to which a liquid is subjected we may use the relation

$$\phi_o W_o = R' T \lg p_1/p_2$$

where ϕ_o represents the value of the hydrostatic pressure of the pure liquid, the pressure of the atmosphere being assumed constant, and W_o is the specific volume of the liquid which may be assumed constant and equal to unity. But, assuming the vapour obeys Boyle's Law, and the hypsometric formula, we have

$$\lg p_1/p_2 = \lg \sigma_1/\sigma_2 = -gh/k$$

where σ represents the density of the vapour and h is the distance between the points where the pressures are p_1 and p_2.

whence $$\varphi_o W_o = -R' Tgh/k \qquad (9)$$

In C.G.S units, $k = 7{\cdot}80 \times 10^9$

$R' = 84{\cdot}7 \times 10^6 \div 18$ (the mol. weight of water vapour)

$g = 981$, T (supposed constant)=300°

Whence, collecting the constants and substituting, we get,

$$\phi_0 = Kh \qquad (10)$$

K = 177·6 when h is measured in centimetres and 5413 when measured in feet.

[1] Briggs, Shantz. *U. S. Bureau Plant Industry Bull.* 230, 1912.

[2] Trouton. *Proc. Roy. Soc.*, LXXVII A (1905), p. 292.

Table I shows corresponding values of θ, M, ϕo and ha, a being supposed equal to unity.

TABLE I.

θ	M	ϕo in atmospheres	ha (in feet,
5·0	0·07	0·00890	1·623
7·0	0·24	0·00427	0·777
8·0	0·38	0·00316	0·575
10·0	0·87	0·00186	0·339
12·0	1·64	0·00117	0·301
15·0	3·55	0·00062	0·114
17·5	4·97	0·00043	0·069
20·0	9·37	0·00021	0·039
21·0	10·67	0·00017	0·030
22·0	12·83	0·00013	0·023
23·0	14·84	0·00009	0 017
24·0	17·05	0·00006	0·011
25·0	19·41	0·00004	0·006
26·3	23·47	0·00000	0·000

The curve in Fig. 5 shows the log of ha plotted against values of M corresponding with ϕo calculated from equation 5.

To determine the height above the water table at which a given moisture percentage can be maintained, find the point on the curve corresponding with the value of M required from which h can be calculated for known values of a. Thus when M = 5 per cent. the height at which this moisture content will be maintained in soils, having various values for the average diameter of particle, is shown in Table II.

TABLE II.

Average diameter in mm.	Height to which soil would remain saturated according to Keen	Height at which water content will be 5 per cent. in feet
1·0	0·3	0·694
0·1	3·2	6·94
0·01	31·8	69·4
0·001	317·5	694·0

There appear to exist no satisfactory data for the testing of these relations. It is unfortunate that in the experiments of Buckingham[1] no record of the physical properties of the soils used is given. However, a rough method of testing the equation is possible by comparing the graphs published by Buckingham for the equilibrium distribution of water in 40 inch columns of soil, with

[1] Buckingham. *U. S. Bureau of Soils Bulletin* 38.

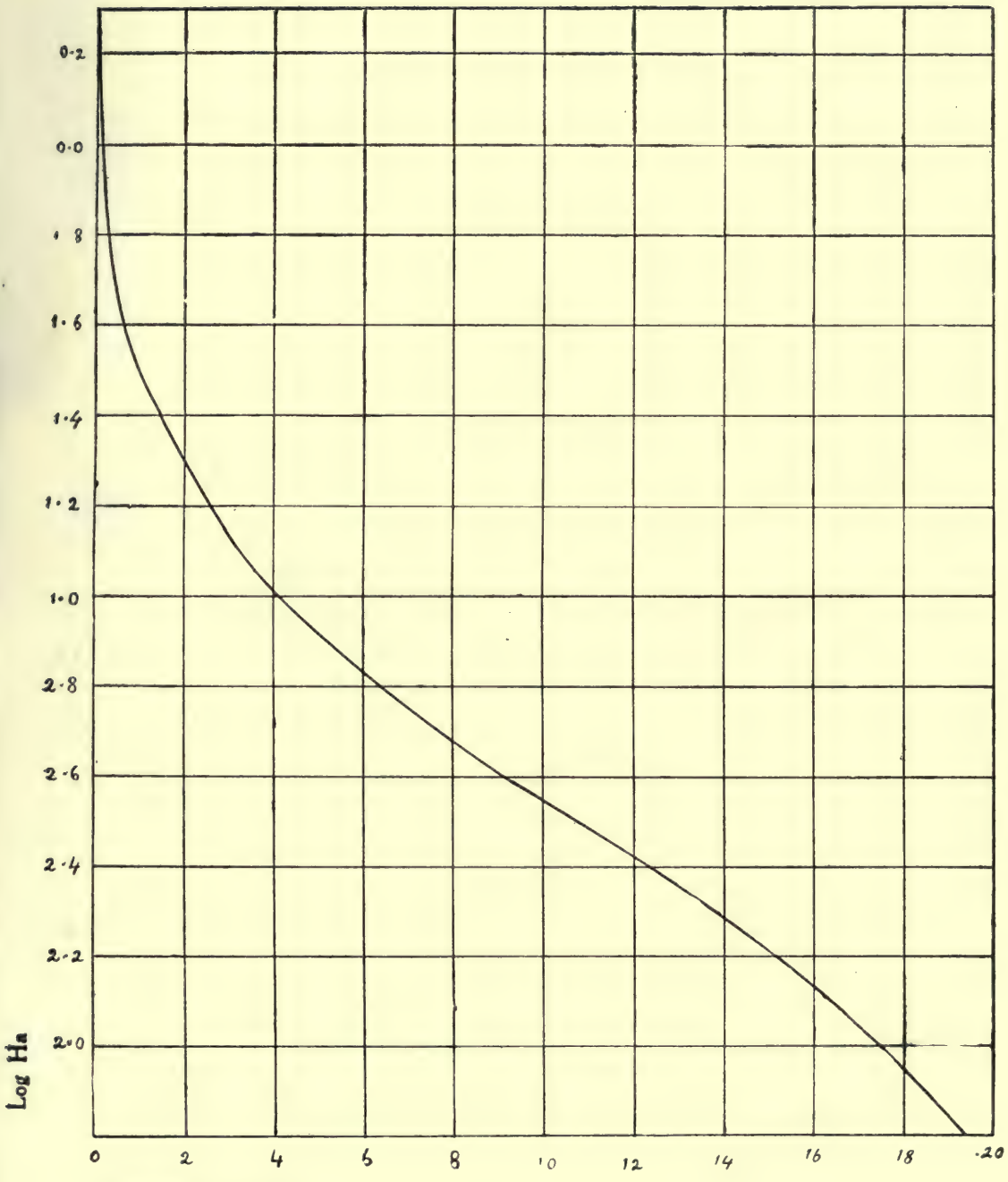

0·2
0·0
1·8
1·6
1·4
1·2
1·0
2·8
2·6
2·4
2·2
2·0
Log Ha
0
2
4
6
8
10
12
14
16
18
20
Moisture per cent.

Fig. 5.

the theoretical curve. Thus in Fig. 12 of the pamphlet referred to, the graphs for three sandy soils are given, namely, New Mexico dune sand, Windsor sand sub-soil and Norfolk sandy loam. Fig. 6 shows the experimental

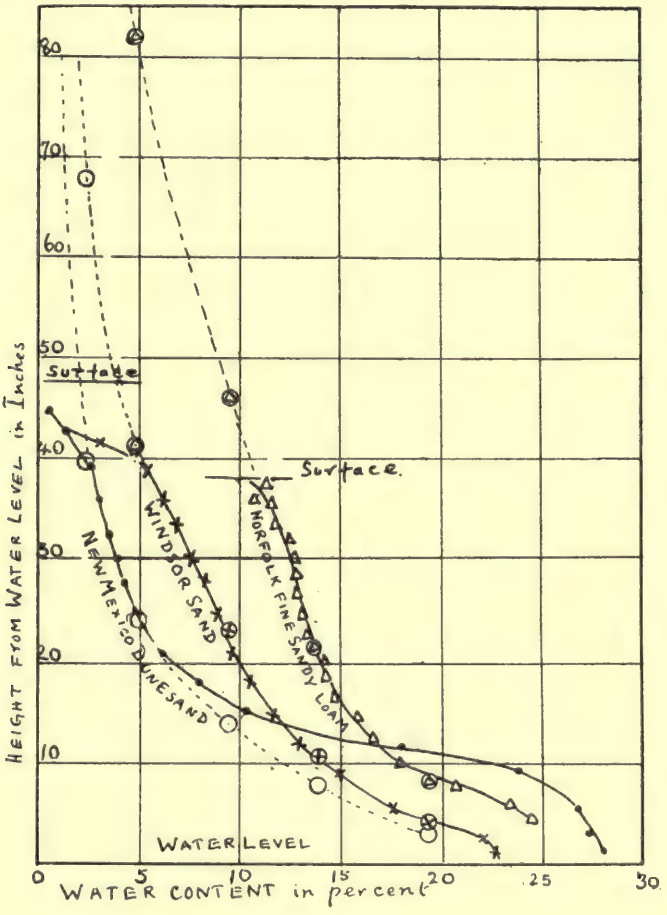


FIG. 6.

Distribution of water in sandy soils after Buckingham, compared with theoretical curves, assuming the following values of d (the mean diameter) Norfolk sandy loam 0·1 mm., Windsor sand sub-soil 0·2 mm., New Mexico dune sand 0·288 mm.

curve compared with those plotted from the above relations assuming that in all cases the soils were packed to the maximum extent, *i.e.*, c=12, and that in the case of the three soils the average radii are as shown below :—

Soil	Radius in mm.
New Mexico	0·345
Windsor	0·20
Norfolk	0·10

It is obvious that the expression is of the right order of magnitude ; in fact, the fit of the curves for the two finer soils is reasonably good over the range measured. In the case of the first however at the higher concentrations of moisture the curves appear to be quite different. This may be due to the fact that with the coarser soils divergencies due to the irregular shapes and sizes of the soil particles will be most evident. In any case for the proper testing of these relations a further enquiry into the relationship between the texture of soils and the factor which appears in the above equation as the average diameter will have to be made. For this purpose a method similar to King's aspirator apparatus for the determination of effective diameter suggests itself and has indeed been applied by Green and Ampt. The further discussion of these relations, and their application to the heavier soils, will be continued, after the treatment of the other factors involved, in the ensuing sections.

The application of the considerations given above to the calculation of the " Mechanical Equivalent " which introduces the effect of gravity, which has so far been neglected, is a less simple matter and is left for treatment on a future occasion.

Appendix.

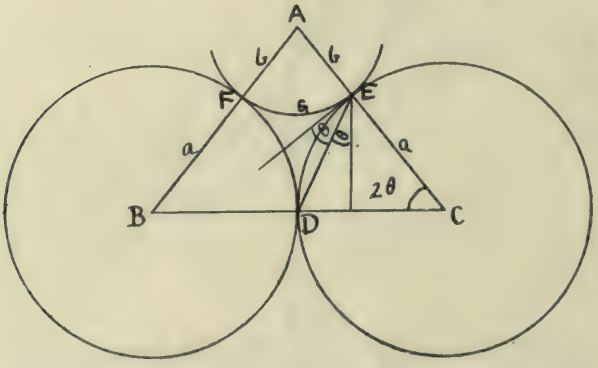


Fig. 7.

Area of triangle ABC $= 1/2\ (a + b)^2 \sin 4\theta$
Distance of C.G. from BC $= 1/3\ (a + b) \sin 2\theta$
Area of the two sectors, CED and BDF $= a^2 2\theta$
Distance of their C.G.'s from BC $= \sin \theta / \theta \times 2/3\ a. \sin\theta$
Area of sector AFE $= 1/2.b^2\ (\pi - 4\theta)$
Distance of its C.G. from BC $= (a + b) \sin 2\theta - \dfrac{\sin (\pi/2 - 2\theta)}{(\pi/2 - 2\theta)} \times \frac{2}{3} b$

If the curvilinear area FGED be A, and its C.G. from BC be γ, then the volume V generated by its revolution about D will be $2\pi\gamma$ A.

$\therefore$ V $= 2\pi$ [1/6 $\cdot$ (a + b)^3 sin2θ $\cdot$ sin4θ — 4/3 $\cdot$ a^3 sin$^2\theta$ — 1/2 (a + b) b^2 $\times$ sin 2θ $\cdot$ (π–4θ) + 2/3 b^3 cos 2θ

$$= \frac{8\pi a^3 \sin^4\theta}{\cos^2 2\theta} \left[1 - \tan 2\theta \left(\frac{\pi}{2} - 2\theta\right)\right].$$

I am indebted to Bhai Balmukhand, M.Sc., for this solution.

(§4) The osmotic pressure of the soil solution.

Referring to equation (5) of section 2, we see that it is necessary to evaluate the integrals

$$\int_{\psi}^{p_o} \times dp + \int_{\pi}^{\psi} U dp + \int_{\phi}^{\pi} U dp + \int_{p_o}^{\phi} W dp = 0$$

where the symbols $\pi\phi\psi$ have been substituted for p_1, p_2 *et cet.* We can thus determine ψ if we can measure π, the *true* osmotic pressure of the soil solution and the hydrostatic pressure ϕ. Although the value of ϕ may be small compared with π at concentrations of *free* water above 1 per cent., the pressure increases very rapidly below this point with soils of average fineness, so we cannot afford to neglect this factor until we are able to determine the amount of free water which will be held by the soil under various conditions. If we know the value of γ, the surface tension of the soil solution, we can estimate ϕ for various values of the free water content, on the hypothesis developed in the preceding section. If it were possible to obtain a truly representative sample of the soil solution it would then be possible to determine π directly. The probably insuperable difficulties which would be met in such an attempt are well known, so we are limited practically to the determination of the *apparent* osmotic pressure by physical measurement of the properties of the soil solution *in situ*. This fact has never been clearly recognised. Thus, both the freezing point method adopted by Bouyoucos,[1] and the vapour pressure experiments of Schull,[2] do not take account of the film tension of the free liquid, and in consequence no accurate comparison can be made of the osmotic pressures of the soil solution in different soils, since the film tension will vary inversely as the average radius of the soil particles. Thus referring to the approximate solution given in equation (7) of section 2, we have $\psi + \phi - \pi = 0$

[1] Bouyoucos. *J. A. R.*, VIII (1917), 195, and XV (1918), 331.

[2] Schull. *Bot. Gaz.*, 62 (1916), p. 1.

It is only if we can determine the values of these factors as functions of the free and absorbed moisture content of the soil, that we shall be able to obtain precise knowledge of the conditions under any particular circumstances. Thus we may write provisionally,

$$\phi \propto \frac{\gamma}{a} f' \left(\frac{1}{UM_1} \right) \tag{1}$$

where M_1 represents the free water in the soil.

$$\pi \propto mRT/UM_1 \tag{2}$$

where m is the number of molecules of dissolved salt in 100 gs. soil.

$$\psi \propto b f'' \left(\frac{1}{XM_2} \right) \tag{3}$$

where M_2 is the adsorbed water, b is a constant proportional to the colloid content of the soil, and as shown by Ostwald and Mundler,[1] n is an exponent which will probably lie between 3·5 and 4·0. Then

$$b f'' \left(\frac{1}{XM_2^n} \right) + \frac{2\gamma}{a} f' \left(\frac{1}{UM_1} \right) = \frac{mRT}{UM_1} \tag{4}$$

If we can confirm the hypothesis involved in the above expressions, and also assume constant, or determine the variation of α, b, γ m, U and X with M and T, we shall be in a position to deduce an expression which will give a complete account of the water in the soil.

We may first examine equations (1) and (2) to see how far practicable physico-chemical measurements will enable us to confirm the expressions.

Reference has already been made to the freezing point method of determining the apparent osmotic pressure of the soil solution. This, while appearing to be fairly accurate, has the disadvantage that it will only allow us to gain a knowledge of the conditions in soils near the freezing point of water. Schull's method of estimating the vapour pressures in soils has the disadvantage that it is dependent on the physiology of the semi-permeability of the testa of seeds, and is open to the objection that the semi-permeability of a seed may vary with the nature of the soil solution with which the seed is placed in contact. Moreover, since the moisture relations in soils will depend on their degree of packing, it will be advisable to adopt a method in which this variable can be measured. An attempt is consequently being made to determine the actual vapour pressures in soils by purely physical methods. For this purpose, the aspiration method of Walker perfected by Berkeley and Hartley has been selected. It has not yet proved possible to overcome all the practical

[1] Ostwald and Mundler. *Koll. Zeit.*, XIV (1919), p. 7.

difficulties met with in an attempt of this sort, and the results so far obtained are subject to errors which preclude any advantage in the publication of the results obtained.

Besides these absolute measurements, an attempt has also been made to measure the magnitude of the swelling pressure in the soil. In order to check these results a series of experiments has been designed whereby direct comparisons of the moisture equilibrium can be made under varying conditions of moisture content, packing, and salt content. Thus, if two quantities of a soil, packed to the same extent, are separated by a semi-permeable membrane and allowed to come to equilibrium, since the vapour pressures must be equal, from (§2.6) we have $UX(\phi_1 - \pi_1) = U_2(\varphi_2 - \pi_2)$ and

$$\psi_1 X_1 = \psi_2 X_2$$

If then we substitute the tentative expressions for $\phi\ \pi$, and ψ given in equations (1), (2) and (3) above, we obtain the following relations,

$$U_1 \left[\frac{2\gamma_1}{a_1} f'\left(\frac{1}{UM_1 - \kappa_1} \right) - \frac{nRT}{M_1 - \kappa} \right] = U_2 \left[\frac{22}{a} f'\left(\frac{1}{U_2 M_2 - \kappa_2} \right) \right] \quad (5)$$

This assumes that the osmotic pressure of the soil to which no salt is added is zero. κ is used to represent the weight of water in the colloid phase, and since the vapour pressures in the two soils must be equal

$$p_1 = p_2, \text{ so } \psi_1 = \psi_2, \text{ and } \kappa_1 = \kappa_2$$

Thus assuming that γ does not vary with the concentration or that we know its variation, and similarly, that α is known, provided we can determine the variation of the vapour pressure of the soil with water and salt content, we shall have sufficient data to test the equations completely. The assumptions are however so great that it will probably only be possible to use equation (5) in a qualitative way. Firstly, we have no right to assume that we can rely on the value of m, the number of molecules of salt added per 100 grams of soil, since adsorption may take place, or that we can cancel out the partial osmotic pressure of the salts already in the soil, from the two sides of the equation. Moreover, any semi-permeable membrane which it will be possible to prepare artificially in order to suit the requirements of the experiment will certainly not be semi-permeable with respect to all the dissolved salts in the soil. We shall thus have conditions such as have been discussed by Donnan, and which he terms membrane equilibria. Altogether the system appears so complex as almost to discourage any attempt at the experiment. Moreover, it must not be forgotten that the most perfect semi-permeable " membrane " in nature is the vapour phase. Thus at first sight it would appear that by far the most promising method of attacking the problem would be by allowing soils of different salt

contents to come to equilibrium in atmospheres containing varying amounts of water vapour. Experiments will be described in which this method is adopted and which should enable the equation developed above to be tested under the best conditions, but it may be pointed out, if any justification is needed for the membrane experiments, that the attainment of equilibrium in the soil through the vapour phase is an extremely slow process, and that, in nature, movements of water of any practical importance will undoubtedly take place through the free liquid or colloid phases. Moreover, since the soil itself can at times act as an imperiectly semi-permeable membrane, as observations made in the course of the experiments to be described, and the work of Lynde and Bates,[1] show, and since, as again will be demonstrated experimentally, unequal distribution of soluble matter in the soil, coupled with the functioning of the soil as an imperfect semi-permeable membrane, brings into play osmotic forces which are of particular importance in considering the dynamical aspects of the problem, even if these membrane experiments provide no sure basis for quantitative discussion in the present state of our knowledge, valuable qualitative results may be expected.

It will, therefore, be as well to consider along the lines adopted by Donnan[2] the effect which the partial permeability of the membrane to the more diffusible salts of the soil will have on the results. As has been pointed out above, if any unequal distribution of the soil salts results from membrane action we shall be unable to assume that the total effective osmotic pressure will be given by the term $mRT/M\text{-}\kappa$. Moreover, there is in addition the error involved in adsorption of salt by the soil colloid. This error we should probably be justified in neglecting as all evidence tends to point to the fact that adsorption of electrolytes by the colloids of the soil is almost invariably attended by the liberation of an equivalent amount of previously adsorbed ions.

Donnan's theory has only been worked out for the simple cases of univalent ions in which either one or no ions are common. In a case such as the equilibrium across a membrane of salts such as calcium ferrocyanide on the one side and sodium chloride on the other, the equations which can be developed by thermodynamical reasoning are of the third order in x and y, the amounts of sodium and chlorine ions respectively which diffuse across the membrane, and are consequently too complex to admit of any useful solution. It can be readily seen however that any changes which occur due to the partial permeability of the membrane must result in a diminution of the effective osmotic

[1] Lynde and Bates. *Jour. Phys. Chem.*, XVI (1912), 759.
[2] *Zeitsch. f. Electrochemi*, XVII (1911), 572.

pressure. By comparing the results obtained with an electrolyte such as calcium ferrocyanide on the one hand, and a non-electrolyte like cane sugar, on the other, it will be possible to obtain some evidence of any existence of this selective distribution of soil salts, which would be of the greatest significance in considering the retention by the soil of useful and harmful salts.

(§5) Experimental.

As mentioned in the introduction, it is only intended to give in this section a brief description of the methods adopted for the measurement of some of the factors necessary for a more or less qualitative test of the relations deduced in the foregoing sections, and it is hoped to publish a detailed description shortly. The work described below has been confined to the examination of one soil only, the mechanical analysis of which is as follows :—

	Soil No. (L2), Square 10, Lyallpur.
Fine gravel	.. 0.27
Coarse sand	.. 5·61
Fine sand	.. 37·71
Silt	.. 25·11
Coarse silt	.. 21·47
Clay	.. 9·83
Total	.. 100·00
Moisture equivalent ..	.. 22·99
Hygroscopic co-efficient	.. 2·433

The partition experiments.

Fifty grams of the soil under investigation, a large sample of which had been previously mixed with the required amount of water or solution, were weighed out quickly and placed in a specially constructed steel cylinder provided with a loosely fitting plunger. A pressure previously fixed upon is then applied by means of a hydraulic press, and the discs of soil so formed quickly taken out and placed in airtight jars.

After many failures it has been discovered that a copper ferrocyanide membrane can be deposited on a particular brand of dialysis parchment paper which appears to be perfectly impermeable to calcium and potassium ferrocyanides, and to cane sugar. This was done by forming the paper into a cylinder which was stuck by marine glue on to two pieces of glass tubing of about one and a half inches diameter. One of the glass tubes is closed at one end and into the vessel so formed a strong solution of potassium ferrocyanide is poured and the whole surrounded with a copper sulphate solution. Electrodes were then placed in the inner and outer

vessels and a weak current passed for several hours. It was found that although no great increase in the resistance of the membrane to the passage of the current took place, an even coherent film was deposited which proved quite satisfactory. The paper without the deposition of this film was quite useless, if the moisture in the soil was high, but appears to prevent the movement of salt entering at low concentration of moisture. This is of interest as it points to the fact which has already been confirmed experimentally, that the soil itself at low concentrations of moisture will act as a semi-permeable membrane. The membrane so prepared is then repeatedly washed in pure water, and after cutting into circles of the right diameter kept moistened between folds of filter paper. Two discs of soil, one made up with pure water, and the other with a solution of the strength required to bring the total moisture content of the two discs and the salt content of one, to a predetermined value, are then separated by a membrane and kept in contact by means of glass discs upon which are placed circular brass pieces provided with three hooks which serve to stretch three rubber bands. The whole assembly is then placed in an airtight jar and kept at constant temperature (32° C.) for about four days. At the end of this time the discs are separated and quickly transferred to weighing bottles and weighed. They are then dried to constant weight in a vacuum oven at 100°.

Table III shows a typical series of results obtained with soil B, pressed to ten atmospheres.

TABLE III.

Series	M_1	M_2	S	P_1	P_2	S_o	R	c
A	3·117	6·440	2·557	25·7	53·2	11·1	2·966	39·70
B	3·282	6·716	2·564	26·1	53·5	20·4	2·046	38·82
B	3·782	6·712	2·144	29·9	53·1	17·0	1·775	31·94
A	3·762	6·750	2·134	29·7	53·4	16·9	1·794	31·62
B	4·153	6·365	1·724	33·9	52·0	14·1	1·533	27·08
A	4·156	5·670	1·289	37·4	51·0	11·6	1·364	22·73
B	4·419	6·037	1·294	37·6	51·4	11·0	1·366	21·43
C	4·810	6·066	1·176	39·9	50·3	9·3	1·261	19·39
C	5·090	5·870	0·943	42·8	49·3	7·9	1·153	15·06
D	5·561	6·610	1·140	42·1	50·0	7·9	1·187	15·73
C	5·252	5·749	0·471	45·8	50·1	4·1	1·095	8·19
A	5·130	5·290	0·434	47·3	48·7	4·0	1·031	8·20
D	5·750	6·103	0·493	46·6	49·4	4·0	1·060	8·56
D	5·655	5·721	0·253	48·6	49·2	2·2	1·016	4·48

In the first three columns, M_1, M_2 and S represent respectively the weights per 100 grm. of soil of water (M) and salt(S), (M_1) referring to the disc containing water only, and (M_2) the disc containing water and

salt. The next three columns give these figures worked out on the basis of water+salt=100. The last two columns give the ratio of the concentration

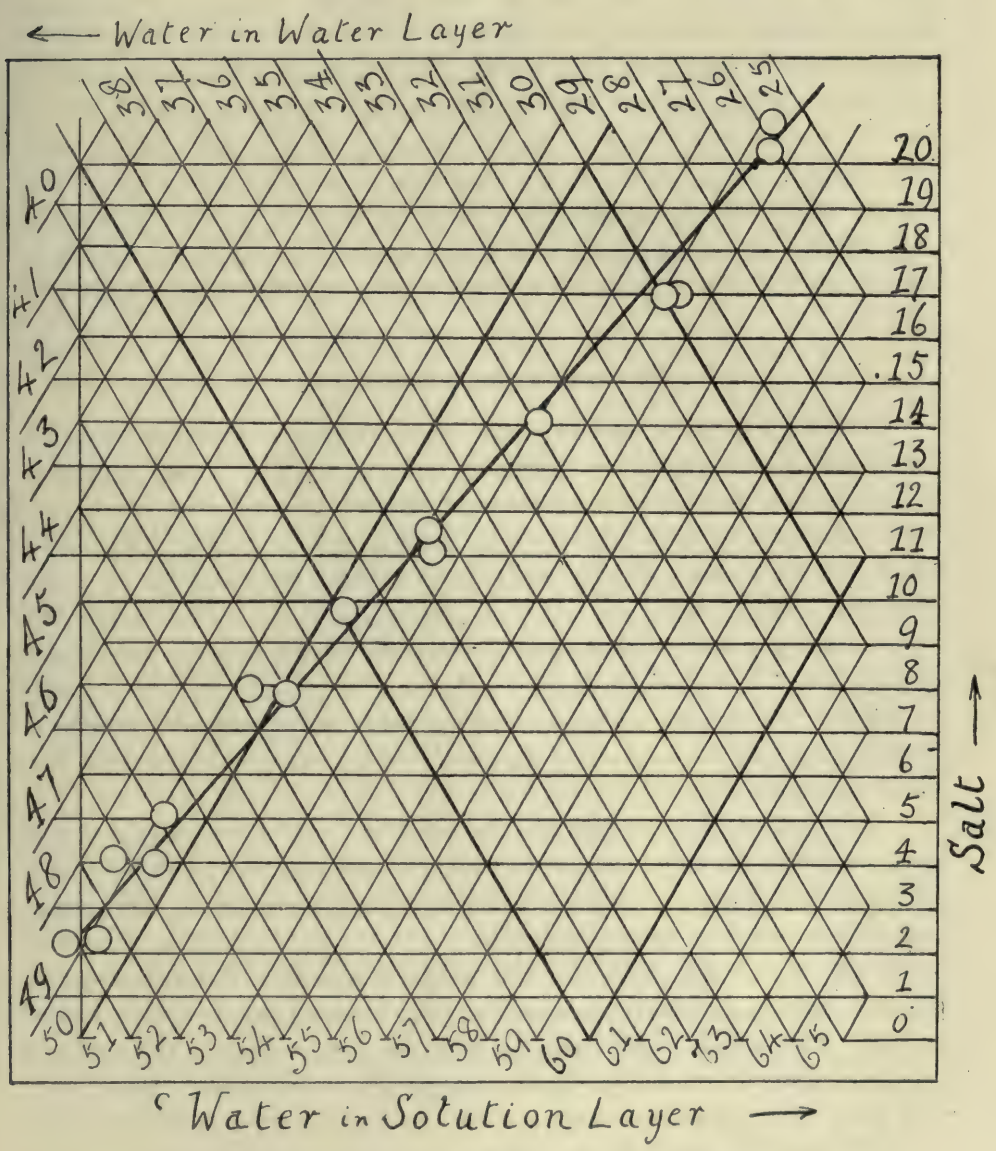


FIG. 8.

Showing partition of water between two soils, one of which contains salt.

of water in the two layers, and the concentration of salt in grams per 100 grams of water. In Fig. 8, P_1 P_2 and S_o are plotted on a system of triangular co-ordinates, from which the distribution of water

and salt in 100 grams of solution can be read off. It will be seen that the distribution follows a straight line law, but that the origin of the curve does not lie at the point where there are equal amounts of water in the two layers. Similar results have been obtained with sucrose solutions, the figures for which will be published subsequently. No explanation can yet be given of this point. A large amount of the error of the observations is probably due to the fact that it is extremely difficult to make up the discs all with the same concentration of moisture: in the experiments recorded above the water content of the discs varied between 5 and 6 per cent. on the total amount of soil. With higher concentrations of moisture at this amount of compression, some water would be expressed from the soil with the higher concentrations of salt.

The compressibility experiments.

The compressibility measurements were performed with the same piston and cylinder as was used for making up soils for the partition experiments. A Tangye press working up to a pressure of 90 tons on an $8\frac{1}{2}''$ ram was used. Two pressure gauges by Schaeffer and Budenburg were used working up to about 180 atmospheres, beyond which point it was not considered safe to go. No means were available for standardizing these gauges, so until this is done, the measurements recorded below must be regarded in the light of preliminary experiments. A diagrammatic representation of the apparatus used is given in Fig. 9. The amount of compression was measured by means of an optical lever as shown in the diagram by means of which a compression of 0·001 cm. could be measured.

The method of procedure was to weigh out a known quantity of soil containing the requisite amount of water or salt solution. This was then placed in the cylinder, the piston inserted, and placed in the press. The mirror was then adjusted to bring the spot on the scale and the pressure increased until the manometer registered the pressure required. Subsequent small increases were made until the pressure remained constant and the spot no longer moved. This usually took about an hour for each reading. The readings so obtained were corrected for the compressibility of the piston. No account was taken of any possible expansion of the cylinder. In any case the correction would be small as the thickness of the cylinder wall was over two and a half inches. The diameter being thus assumed constant the volume of the soil at any point is proportional to the thickness. At a point depending on the percentage of moisture in the soil and also on the amount of salt in solution, the compressed soil becomes saturated, and water flows out from between the

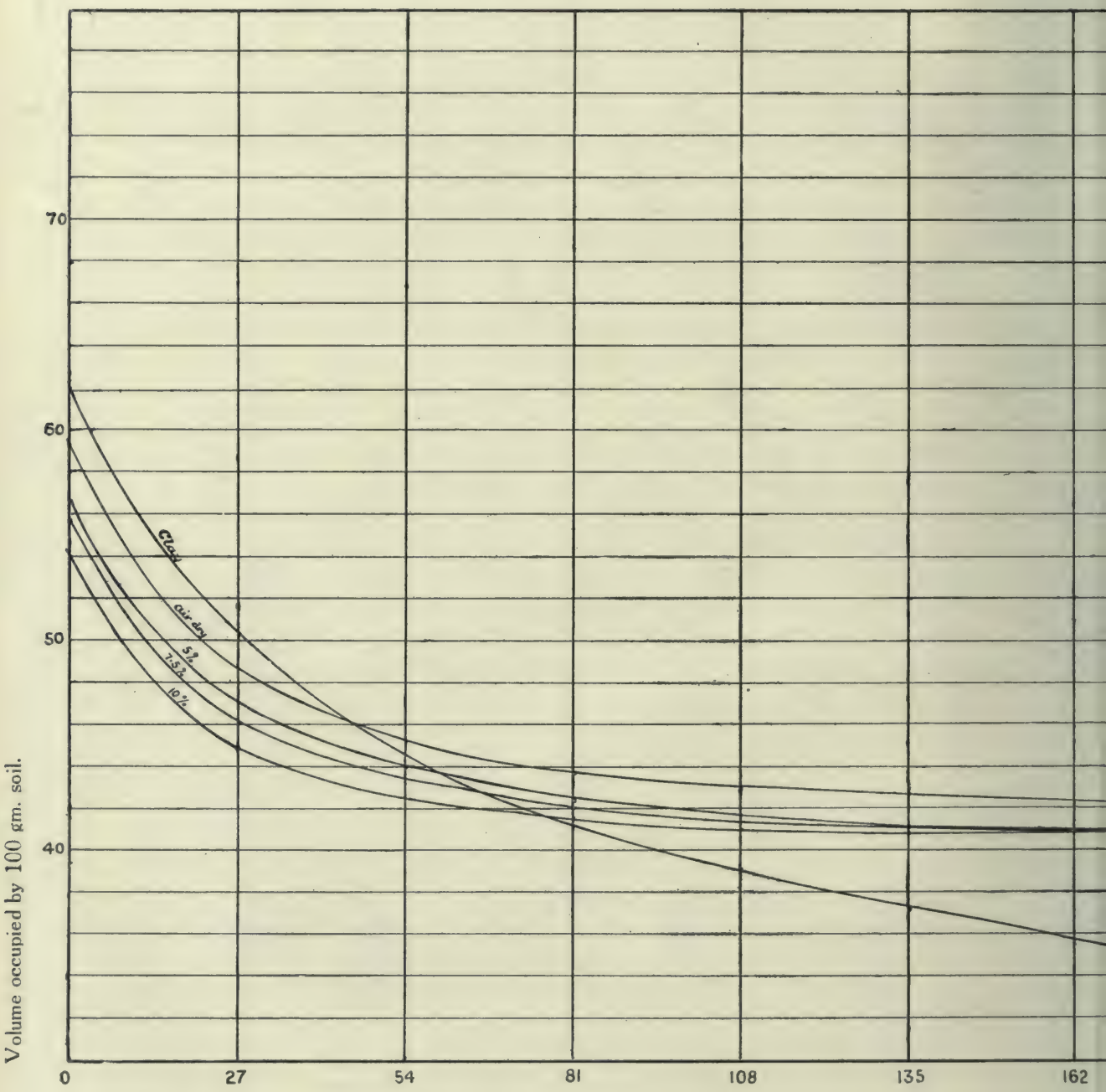


Fig. 10 Showing compressibilities of soil and clay.

cylinder and the bottom plate and into the clearance between cylinder and piston. It will be of interest to determine the exact point at which this occurs,

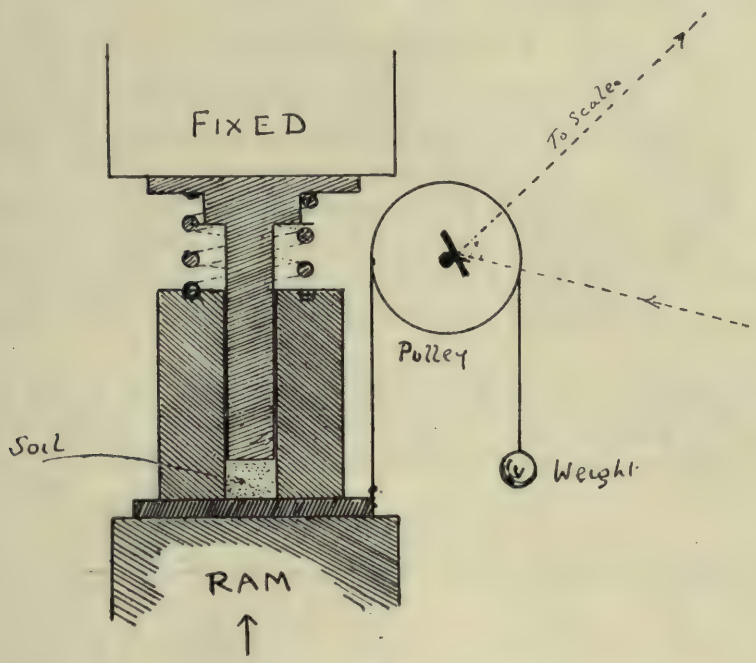


FIG. 9.

but so far no satisfactory method has been devised and only qualitative observations have been possible.

A typical series of smoothed curves is reproduced in Fig. 10. It will be seen that the apparent volume occupied by the soil under any pressure depends on the amount of moisture present, the more water the soil contains, the greater the amount it is compressed. Unless it is possible to determine the amount of pore space at each stage in the compression of the soil, it is obvious that for purposes of estimation of the swelling pressures of the colloid, the experiments will be useless. Moreover, when the pressure is released any free water pressed out will be absorbed again by the colloid. Attempts have been made to measure the reversible changes of volume of the soil with varying moisture contents, but so far have not been successful. Since again the soil will contain free water it will be impossible to determine the pore space by immersion. On this account it was considered advisable to determine the compressibility of " pure " clay isolated from the soil under examination by sedimentation. The curve is shown in the same diagram. It will be seen that

the compressibility of the clay is still very considerable when, with the soil, it has fallen to about the value which would be expected for the crystalline particles contained in it.

The absorption experiments.

If a solute can be discovered which is not absorbed by the soil it can be used as a reference substance for the determination of any change in concentration produced by removal of solvent when a soil is allowed to come to equilibrium. Thus on adding soil to a sucrose solution there is a removal of water by the soil colloids which will cause a corresponding increase in the concentration of the sucrose. It should thus be possible to determine the relation between moisture content of the colloid and the osmotic pressure of the soil solution.

The figures given in Table IV and which are plotted in Fig. 11 were obtained by allowing a known weight of soil to attain equilibrium with a known weight of sugar solution of known strength at 32° C.

TABLE IV.

C_o Initial concentration	C_1 Final concentration	x Soil gm.	y Sugar sol. in grams	X Gm. water absorbed per gm. of soil
9·383	9·897	20·1429	40·0570	0·102
18·550	18·640	19·9468	53·5341	0·082
18·012	18·660	20·0629	41·9895	0·073
27·080	27·500	20·0810	53·7759	0·047
40·685	41·110	20·0315	45·0864	0·031
43·962	44·340	20·0481	46·3982	0·023
47·876	48·490	20·0412	48·6505	0·033
48·670	49·070	20·0043	60·2483	0·024
56·04	56·360	20·1321	61·8858	0·018

The solution was then removed and the concentration determined by the polarimeter. The columns headed C_o and C_1 give respectively the initial and final concentrations of sucrose expressed as gm. of sucrose per 100 gm. solution. x and y give the weights of soil and solution mixed, from which the values of X in the last column were calculated. The errors involved in this determination must be very great despite the utmost care taken in the work, as small differences in concentration of strong solutions have to be measured. The results are, however, sufficiently accurate to allow of fair certainty of the course of the curve, but can probably be improved on by the adoption of a more refined method of estimation of the cane sugar. When

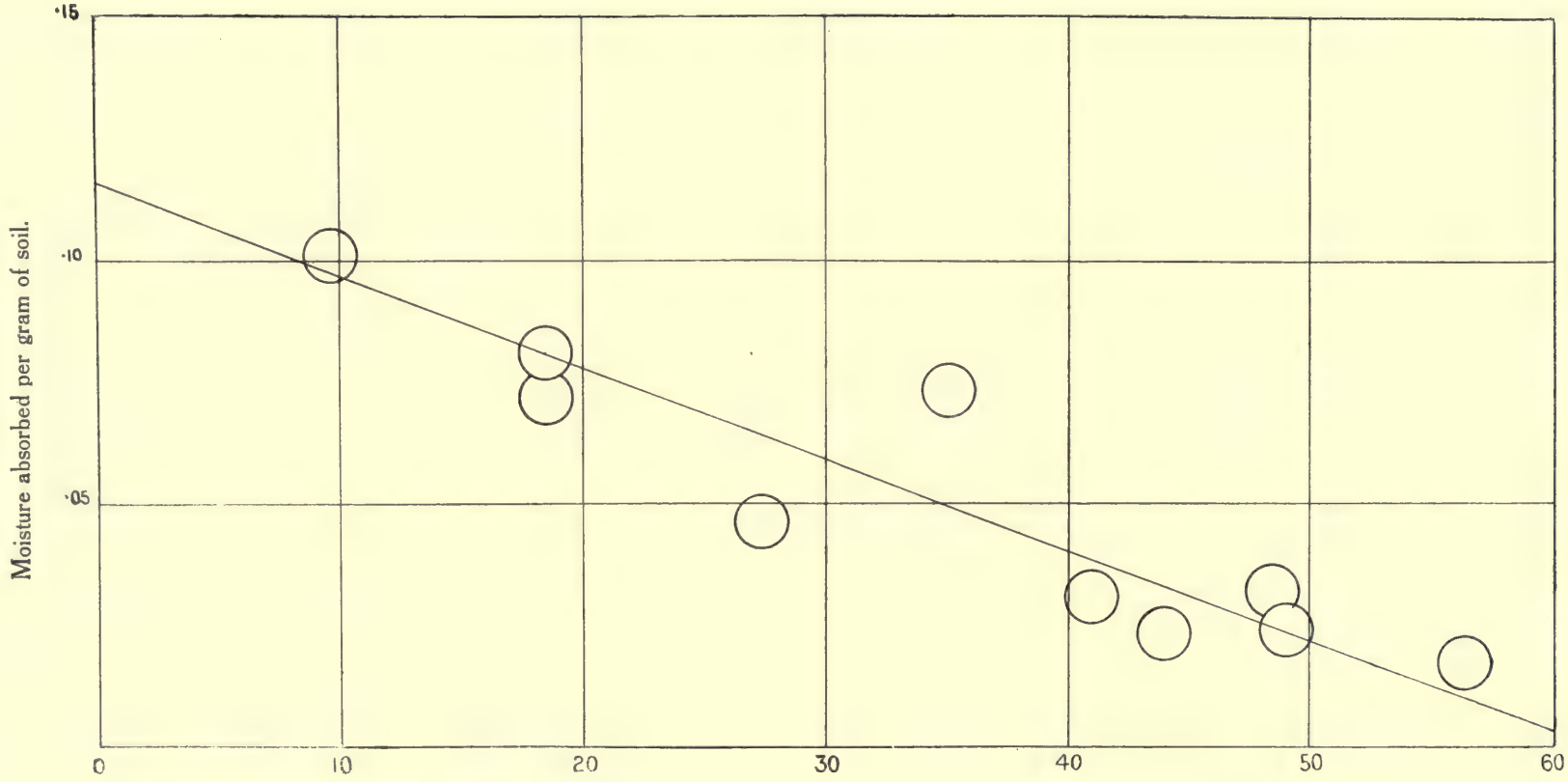


Fig. 11. Showing the absorption of water by soil in sugar solutions of various strengths.

the curve is extrapolated to zero concentration it is found that the soil absorbs 11·5 gm. of water per 100 gm. of soil.

The hygroscopic co-efficient of the soil, *i.e.*, the amount of water absorbed per 100 gm. soil when in equilibrium with a saturated atmosphere, is 2·43. One might expect that the amount of water absorbed by the soil colloids from a saturated vapour phase would be the same as that taken up from the pure solvent which is in equilibrium with the vapour, and theoretically, if no surface forces due to the state of division of the colloid are considered, this should be the case. Thus Alway (*J. A. R.*, Vol. VII, 350, 1916) states, " Theoretically, actual equilibrium would not be obtained until the moisture content of the soil equalled that of the same soil in actual contact with water, but the time required for this is so great that this theoretical consideration does not affect the present discussion." Actually, as these experiments show, the amount of moisture absorbed by the soil when in contact with the water is much greater than that absorbed from the vapour phase. The ratio of these amounts, 11·5/2·43=4·73, is remarkably near the factor 4·26 in the Briggs-Shantz empirical formula connecting moisture-holding capacity of soils with their hygroscopic co-efficients.

This relation can be expressed as follows,

[Moisture-holding capacity] = [Hygroscopic co-efficient]×4·26−21·0

with which are to be compared the value of the factor (4·73) determined from the absorption experiments, and the value 23·46 deduced theoretically from equation (7) of §3.

If these results are confirmed by further work on different soils, it appears that we shall be in a position to form a much clearer idea of the true physical basis of these " constants." It can scarcely be accidental that both the theoretically deduced " free " moisture capacity of a soil and the experimentally determined ratio of the absorbed water to the hygroscopic co-efficient should agree so closely with the empirical equation evolved by the examination of a large number of soils. How far the specific character of the colloids of different soils will cause variations in the value of the factor from that calculated by Briggs and Shantz only further investigations can show.

With a knowledge of the variations of the " bound " moisture content of a soil with the osmotic pressure of the " free " solution in equilibrium with it, it will be possible to extend the calculation of " capillary " rise, given in §3·10, to the case of a soil containing a colloid. It is considered, however, that the curve produced above is not sufficiently accurate for the purpose, and, moreover, it will be necessary to examine the curve for clays contained in various soils of different geological origin before any generally applicable

relation can be deduced. The consideration of this point is, therefore, postponed.

From theoretical considerations it appears that if the equilibrium moisture content of a soil in contact with a liquid is not the same as that attained when contact is only with the vapour phase, which is itself in equilibrium with the liquid, the only explanation which will account for the fact is that a new phase is formed. Thus we may suppose that the hygroscopic co-efficient refers to the equilibrium of only two phases, colloid and vapour, while the moisture-holding capacity and the mechanical equivalent must be determined by the equilibrium of vapour, colloid, the free liquid phase and one other. It is suggested that besides the free water which will presumably obey the laws deduced in section (3) there is also what may be called vesicular water retained in the reticulated structure of the colloid.

In order to distinguish clearly between the states in which water exists "free" and "unfree," it will be as well to consider as "free" water only that which has a free surface; the remainder may be distinguished as "gel" water and vesicular water. At the hygroscopic coefficient a soil will thus only contain "gel" water. The factor (4·2) by which it is possible to calculate the total gel and vesicular water in equilibrium with water at atmosphere pressure may be referred to as the "vesicular co-efficient." The vesicular water must be maintained in equilibrium with the colloid, free water and vapour phases by the mechanical pressure exerted by the colloid structure, and moreover, if this colloid behaves as a semi-permeable membrane to dissolved matter, osmotic forces will also come into play. It is quite possible, of course, that this fourth water-containing phase is crystalline, but, if so, it does not seem probable that the factor would be constant for soils of diverse origin. Many interesting lines of investigation present themselves for the testing of this theory which it is hoped it may be possible to pursue in the near future.

(§6) Conclusion.

Although, it is not yet possible to test completely the theoretical deductions advanced in section (2), some tentative conclusions may be drawn, which are of interest in practical application to agriculture.

In the case of a soil containing no colloid, such as a coarse sand, the behaviour of the soil solution will be determined completely by the average size of the particles and the surface tension of the solution. The composition of the solution draining from such a soil should therefore remain unaltered.

If however a saline water is added to a soil containing colloid, water will tend to move through the colloid phase in order to dilute the solution if its

osmotic pressure is greater than the swelling pressure of the colloid, or the solution will become more concentrated if the reverse is the case. This is well illustrated by the following experiment :—

Two quantities of soil were made up to a moisture content of 7·5 and 5 per cent. and similar quantities with the same moisture contents but containing respectively 20 and 15 per cent. of solution of calcium ferrocyanide. These were pressed into slabs, made up in pairs and separated by parchment paper. The pairs of slabs were surrounded with tin foil and kept in airtight bottles. After various intervals of time a portion was cut off each slab and analysed. The results are shown below :—

Time	Ratios of moisture in slabs $\frac{\text{salt layer}}{\text{water layer}}$		Remarks
	7·5 per cent. moisture 20 per cent. salt	5 per cent. moisture 15 per cent. salt	
0	1·0	1·0	....
4th day	1·20	1·10	No salt moved.
6th day	1·40	1·30	No salt moved.
8th day	1·30	1·20	Salt moved.

It thus appears that the first action is for free water to move across to the salt layer in order to dilute the solution, thus reducing the osmotic pressure and increasing the hydrostatic pressure on the water side. The salt then diffuses back carrying with it water. The final equilibrium will thus be obtained, in the absence of a semi-permeable membrane, when the salt solution is equally distributed throughout, but the rate at which the salt solution will move back may be very slow.

Since the equilibrium distribution of water in a soil is determined by the vapour pressure gradients in the soil atmosphere, the " bound " water of the colloid will have a definite value at equilibrium at each point in the column ; the concentration of the sub-soil water will therefore affect the " capillary " rise, whereas, in the case of a sand, it will only do so in virtue of its concomitan variations in surface tension. Since therefore the solution draining from a soil may be supposed to be in virtual osmotic equilibrium with the colloid at each point, the composition of the solution will be determined by the colloid content. We should expect therefore that the ground water beneath a heavy soil would be more saline than in the case of a light soil.

Again, the rate of movement of a soil solution in a sandy soil should depend only on the gradient of hydrostatic pressure due to film tension, and the viscosity of the solution. In the case of a soil containing colloids however, we have two rates to consider—the rate of movement of water in the colloid phase—and also the rate of movement of the free solution in virtue of its hydrostatic pressure.

The importance of considerations such as these in determining the advisability of shallow and frequent, or heavy and infrequent irrigations need not be emphasized. It would appear that in a light soil where the composition of the drainage water is unaffected, water economy should demand light and frequent waterings. In the case of a heavy soil however, owing to the possibility of the concentration of the soluble matter of the irrigation water by virtue of a rate of diffusion of the water through the colloid phase to drier parts of the soil, greater than that of the free solution, the soil may become saline ; heavy waterings, therefore, seem indicated. Moreover, although in such a soil, the water may penetrate beyond root range, it will still be available to some extent to the crop by upward movement through the colloid phase without carrying up salt.

The above points are not advanced as definite conclusions but only as indications of lines of investigation which are opened up by a clearer consideration of the physical factors involved in the movement of a salt solution through a soil. Before, however, it is possible to deal with the dynamics of these questions, it is necessary to obtain all the information possible of their statics.

SUMMARY.

1. The importance of studying all the factors affecting the movement of water in the soil and particularly the salts contained in the irrigation water, is pointed out.

2. An approximate calculation enables an estimate to be formed of the amount of water percolating from an irrigation area. Considerations of the residual sodium salts applied with the irrigation water and not removed by the crop enable rough conclusions to be drawn as to the average percolation from irrigated fields in the Lower Chenab canal colony.

3. Theoretical relations determining the equilibrium of a " free " solution having an osmotic pressure with the water " bound " in the colloid phase, and the vapour phase, are deduced by thermodynamical considerations.

4. From considerations of surface tension, a relation is deduced between the average size of soil particles and the film tension of water in the soil at various concentrations, by means of which it is possible to calculate the statical distribution of water in a column of soil saturated at its base.

5. The relation of these deductions to the empirical soil " constants " is discussed and a satisfactory result is obtained for the calculation of the moisture-holding capacity of soils.

6. Experimental results are given showing the variation of " bound " water in the colloid of a soil with the osmotic pressure of the solution. Extrapolation to zero osmotic pressure gives a value for the moisture absorbed by the colloid which is 4·7 times the hygroscopic coefficient. On the basis of these results an explanation of the empirical relationship between the moisture holding capacity of a soil and its hygroscopic coefficient is afforded.

7. It is suggested that the " bound " water of the soil exists in two phases which have been provisionally named " gel " water and vesicular water.

8. A preliminary experimental investigation of the compressibility of soils is described, but the results so far obtained do not allow of any deductions being made as to the swelling pressure of the soil colloids, for which purpose it was intended.

9. Experiments are described in which the hydrostatic pressure due to film tension is balanced against the osmotic pressure of a soil solution.

10. Certain tentative conclusions bearing on the composition of the solution draining from soils, and on the economic use of water are pointed out.

LYALLPUR :

September 1920.

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